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The Modeling and Simulation of Underwater Acoustic Energy Exposure Due to Near Surface Explosions on Marine Mammals

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The Modeling and Simulation of Underwater Acoustic Energy Exposure Due to Near Surface Explosions on Marine Mammals

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INTRODUCTION

This paper discusses the development of a simulation tool for predicting the biological consequences from exposure to underwater explosions. During naval live fire exercises, shock waves and intense acoustic energy are released into the surrounding underwater environment. A simulation tool is developed to predict the biological exposure effects from multiple transient acoustic events over a period of time. For this case, an underwater explosion model is coupled with simulation of marine mammal movements in 3-D to record acoustic exposure. Inputs to the simulation include the acoustic environment, marine mammal distribution and movement (including behavioral response if appropriate), number of explosions, and source timeline with locations that can be randomized if desired. Model outputs include positive impulse, peak pressures, and acoustic energy exposures. Shock wave impacts are assessed using the modified Goertner Impulse Criteria (Goertner 1982), peak pressure exposure and hearing hazard predicted using energy flux density exposure verses time (Goertner and Lehto 1996). This simulation can be used as a predictive tool by environmental planners to reduce or eliminate undesirable effects on the environment from multiple detonations. Results are shown for a hypothetical test scenario.

ACOUSTIC EXPOSURE MODEL

An acoustic exposure model was created to accurately predict and assess the impacts of simultaneous or intermittent underwater acoustic events on marine animals. It is a generic exposure model, one that can be used for all types of acoustic sources, but for the example presented within this paper, explosive sources are selected.

The six process components comprising the simulation are:

1. An exercise description including the type of acoustic sources used and their associated use timeline;
2. A physical oceanographic and geo-acoustic dataset for input to the acoustic propagation model for the planned exercise time of year;

3. An acoustic propagation model suitable for the source type to predict energy levels at ranges and depths from the source (SONAR, explosives, air guns, continuous source);
4. Biological data for the test area including information about distribution, abundance, movements, behavioral reactions, and a model of marine species distributions in three-dimensions;
5. A module to combine the acoustic and animal movement information to predict exposures for all animals during an exercise to record a dosimeter record;
6. A post-exercise processing module to evaluate the dosimeter exposure record into percent population exposure statistics for each animal impact criterion (or guideline).

How these six components interact in the simulation is presented in the model process flow diagram in figure 1.

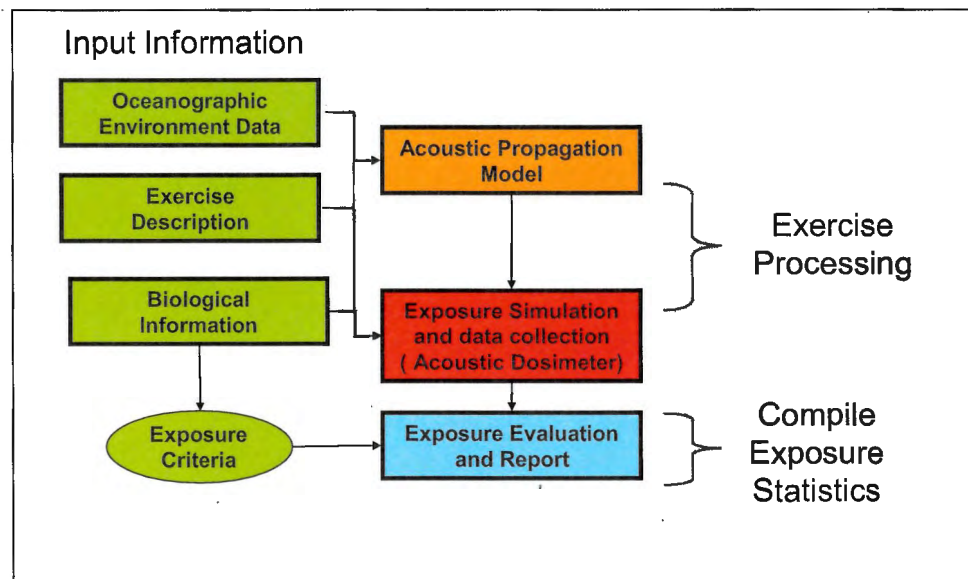


Figure-1. Modeling Process Flow Diagram

EXERCISE DESCRIPTION

A Naval live fire exercise is defined as a military readiness activity involving the bombardment of an unmanned target vessel or vessels using live and inert weapons. The weapons used may be deployed from subsurface vehicles, surface vessels or aerial platforms, depending upon the training objectives. Although the exercise may lead to the eventual sinking of the target(s), the objective is to provide active at-sea training in the entire process of weapons use, including preparation and issue, target evaluation,

selection, acquisition and attack, and battle damage assessment. A live fire exercise is conducted during daylight hours and the duration may range from hours to several days. Targets are towed to the planned location, set adrift, and fired upon until they are sunk. Weapons are typically fired in order of decreasing safety impact footprint as vessels move in closer to the target during the launching sequences.

For the exercise simulation, known acoustic source characteristics (e.g., explosive size) are used to predict the acoustic energy that propagates during intermittent underwater acoustic events (e.g., shock wave, peak pressure, energy flux density, etc.) for a predetermined exercise timeline and source sequence. The Reflection and Refraction Multi-Layered Ocean/Ocean Bottoms with Shear Wave Effects (REFMS) was used to analyze peak pressures, positive impulse, and energy flux effects from underwater detonations associated with a SINKEX. The REFMS model (Britt, Eubanks et al. 1991) calculates the combined reflected and refracted shock wave environment for underwater explosions using a single, generalized model that is based upon Cagniard's linear wave propagation theory convolved with a nonlinear similitude source term for each explosive event. For the analysis presented here, two source types are simulated. The first source is a large explosion of about 100 kg of TNT and the second a smaller explosion of around 30 kg of TNT.

Once the number of source types, number of events, and time intervals for the events are determined, a timeline for the exercise is created. A timeline considers minimum and maximum time between individual events, period of use for each source type, and order of source use. Source events are randomly distributed in time within the minimum and maximum times. This is graphically depicted in figure 2.

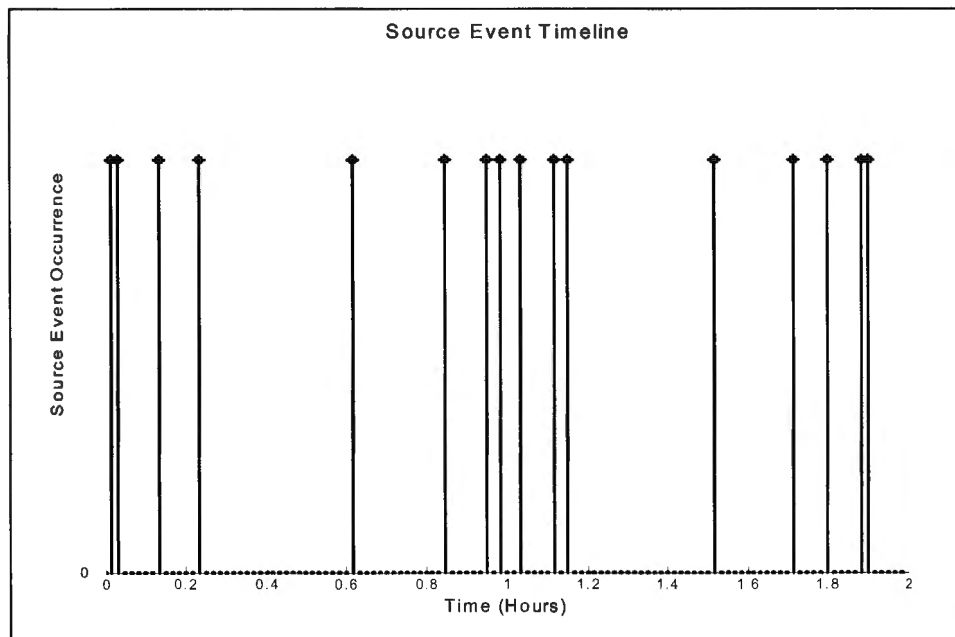


Figure-2. Source Event Timeline

Exposure of the mammals in the test region during an acoustic event is depicted in figure 3. Within the red region, mammals are exposed to 12 psi or greater pressure levels; and within the yellow region, animals are exposed to a harassment EFDL of 185 dB re $1\mu\text{Pa}^2\text{-sec.}$ or higher. Mammals within the yellow and red regions would swim to leave the harassment area.

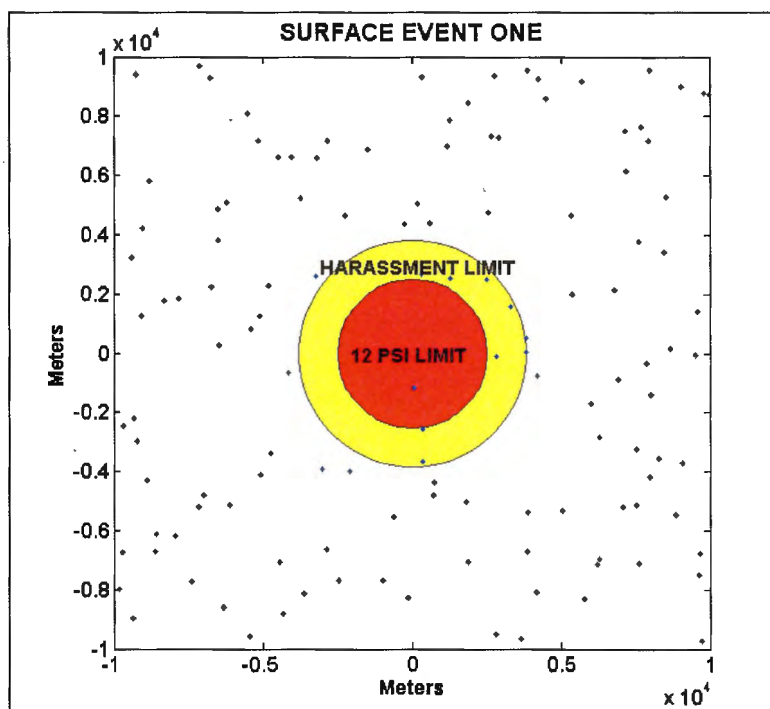


Figure-3. Single Event Exposure Area for Two Exposure Criteria

MAMMAL MOVEMENT

The three-dimensional animal movement simulation is based upon known habitat use characteristics and behaviors specific to the geographic area of species present where the exercise occurs (e.g., swim speeds, migration, feeding, social behavior, depth profiles, etc.). The initial headings and locations for their paths are randomly selected for all animals. Swim speeds are appropriate for the species of animal and a variation of $\pm 10\%$ in speed is assigned to each individual. Behavioral responses to the acoustic exposures can be programmed where appropriate. Types of responses include changes in swim speed, heading, depth, and area usage. Animals are populated within the exercise area at levels determined by the user, but population estimates are usually based on published surveys or peer-reviewed literature. Types of movement avoidance behavior previously considered in this simulation include linear, potential field, or swarm.

An example of a simple linear avoidance model is when mammals that are exposed within a region to a predetermined exposure criteria level, e.g., ≥ 185 dB EFDL, will turn and leave the area at a higher swim speed. When the mammal leaves the behavioral

avoidance area when the acoustic levels are below the criteria, it slows down to its normal swim speed and takes a heading that avoids entering the harassment area again. An example of this model is shown in figure 4 where the paths of several mammals are plotted for the test period. Some animals are within the behavioral avoidance region at the beginning of the test, leave that region, and then swim on another heading after leaving. Several animals are outside of the avoidance region, enter it between acoustic events, leave the area, and then assume another heading when out of the area. The remainder traverse the test region without any behavioral changes.

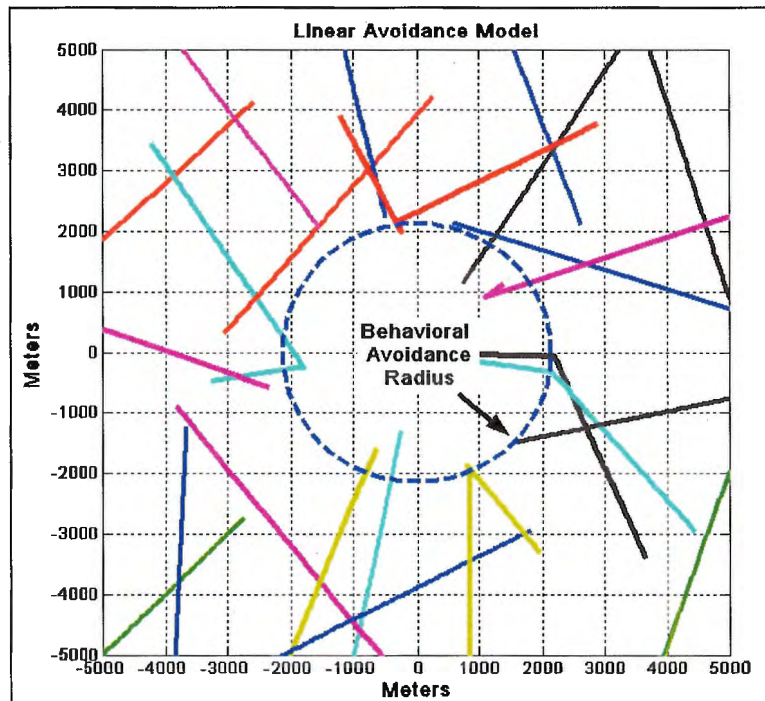


Figure-4. Linear Avoidance Model Mammal Paths

DOSIMETER RECORD

A dosimeter is assigned to each simulated animal and records information pertinent to the acoustic environmental impact assessment. Information collected as a function of time includes:

- Acoustic exposures (sound pressure level (SPL) both total and spectral, energy flux density levels (EFDL) both total and spectral, peak pressure, and positive impulse).
- Position, depth, heading, swim speed, and behavior reaction in the test area and slant range from acoustic events relative to the test area. Absolute position units can also be included as UTM or latitude and longitude.

After the start of the exercise, as individuals move within the environment, mammals are exposed to varying intensities of acoustic energy depending on their location relative to the acoustic events (source and receiver positions). Acoustic levels versus depth and range in the test region are obtained from pre-calculated tables using the selected range dependent propagation model for the sources. Acoustic exposure information is then stored in the dosimeter assigned to each simulated animal over the course of the entire exercise. An example of a dosimeter record for a single animal is shown in figure 5; it indicates the SPL exposure for each acoustic event versus time.

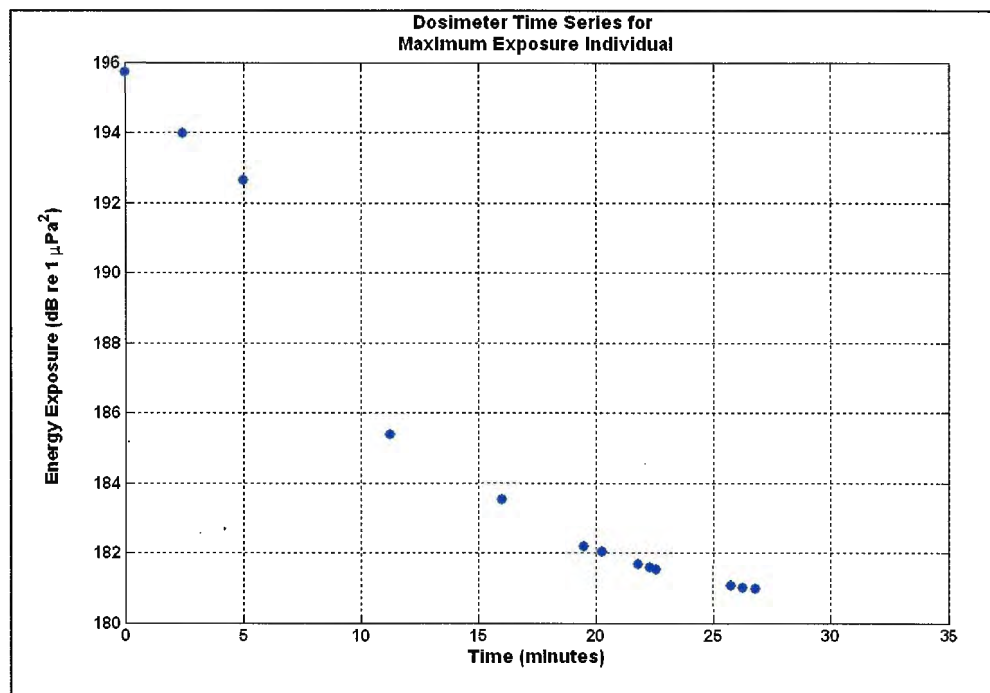


Figure-5. Dosimeter Record of SPL Exposure vs. Time

DOSIMETER ANALYSIS

The final and quantitatively revealing stage of the simulation comes from analysis of the mammal dosimeter records. Information collected in the dosimeters is processed and compared to a set of defined criteria to quantify the impact to the individual animals and to the population at large. Criteria are defined for non-accumulating or accumulating levels during the exercise to predict physical and behavioral impacts.

An exercise was simulated for three large (100 kg) and 13 small (30 kg) explosive events within the test exercise span of 35 minutes and ~2300 individual mammals are simulated. Straight line avoidance behavior is simulated in the mammals as previously described. Over population of the mammal density is used in this case to obtain continuous distributions functions with a minimum of model runs. When the model is run with actual densities, over 100 model runs are required to obtain a continuous exposure distribution.

However additional information is available allowing for confidence intervals to be determined and accuracy of the model results. Probability of rare and unusual events, such as a collision with a source or very high acoustic exposures, can be determined.

Processing criteria for the example consisted of 12 psi or greater pressure exposure and total energy flux density exposure (EFDL) for all individuals. Percent population EFDL exposure distribution functions are calculated as this quantity is additive over the test period assuming no hearing recovery.

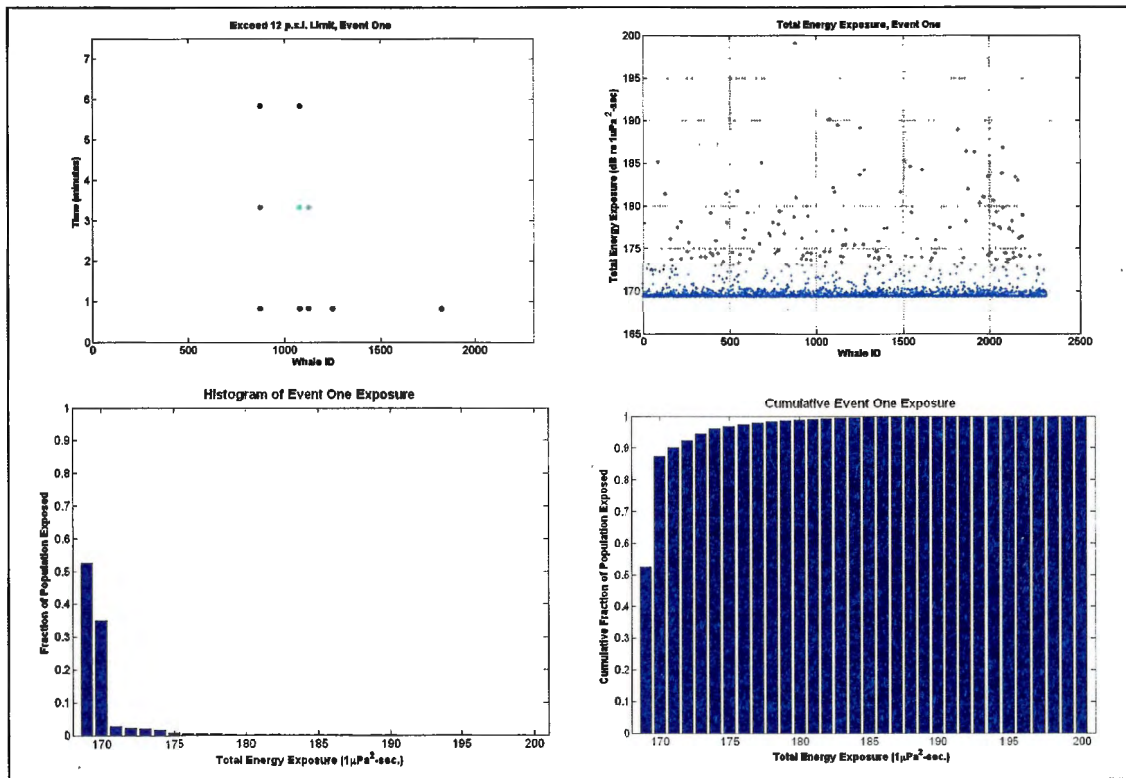


Figure-6. Analysis of Dosimeter for First Source Type (Large Explosive)

Four charts are included in figure 6. The upper left indicates that five mammals were exposed to 12 psi or greater pressure levels with three animals exposed three times. Two other animals were only exposed once and were able to leave the 12-psi region before the remaining large explosive events occurred. The upper right chart presents the cumulative energy exposure of all animals present during the first event. On the lower left, a histogram of the cumulative energy exposures verses percent of the total population. The lower right chart presents a cumulative percentage of the population exposed as a function of energy level.

For the second smaller source, an identical analysis is performed and displayed in figure 7. Only one animal is exposed to the 12 psi levels during the 13 events of this

smaller source. Additionally, the behavioral avoidance of the animals can be observed in the upper right chart as the energy exposures are clustered in a band.

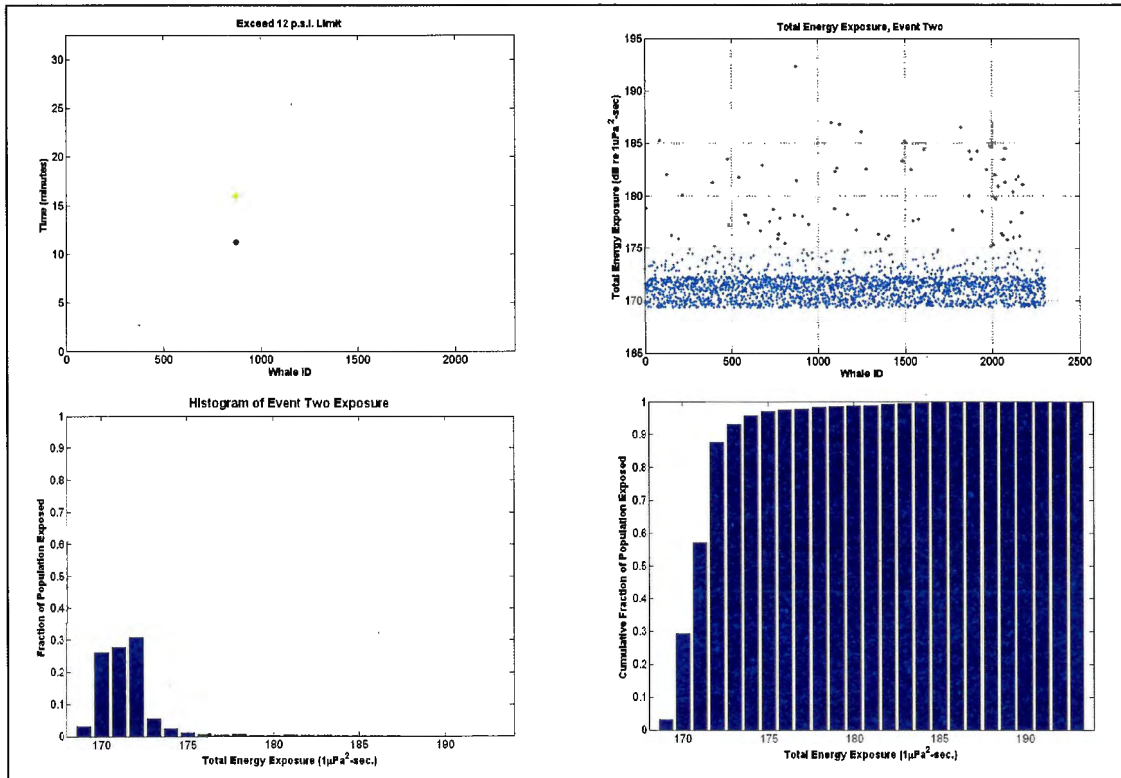


Figure-7. Analysis of Dosimeter for Second Source Type (Small Explosives)

Of final interest is the cumulative effect of all sources over the test period presented in figure 8. This presentation is identical to the previous figures except for the upper left chart. In this case, the upper left chart shows the distance the mammal is from the source location as a function of range versus time. Indicated by the red asterisks are the time of the acoustic events and the radius of the 12-psi exposure region. The maximum exposed individual, has five 12-psi exposures, but due to its avoidance behavior, has moved away from the source location and avoids further 12-psi events. The individual keeps vacating the area for 25 minutes, until it at last is outside the behavioral avoidance region of the small explosive source. At this time, the animal then turns and swims in another direction away from the source location.

As the dosimeter contains a complete acoustic exposure record, hearing recovery functions as well as audiogram curves can also be introduced at this stage to access the accumulating dose for TTS and PTS determinations. Introduction of hearing recovery would reduce the number of individuals exposed to levels that produce TTS and PTS. This flexible approach allows predictions of increasingly greater fidelity as knowledge of marine species hearing and behavioral response increases.

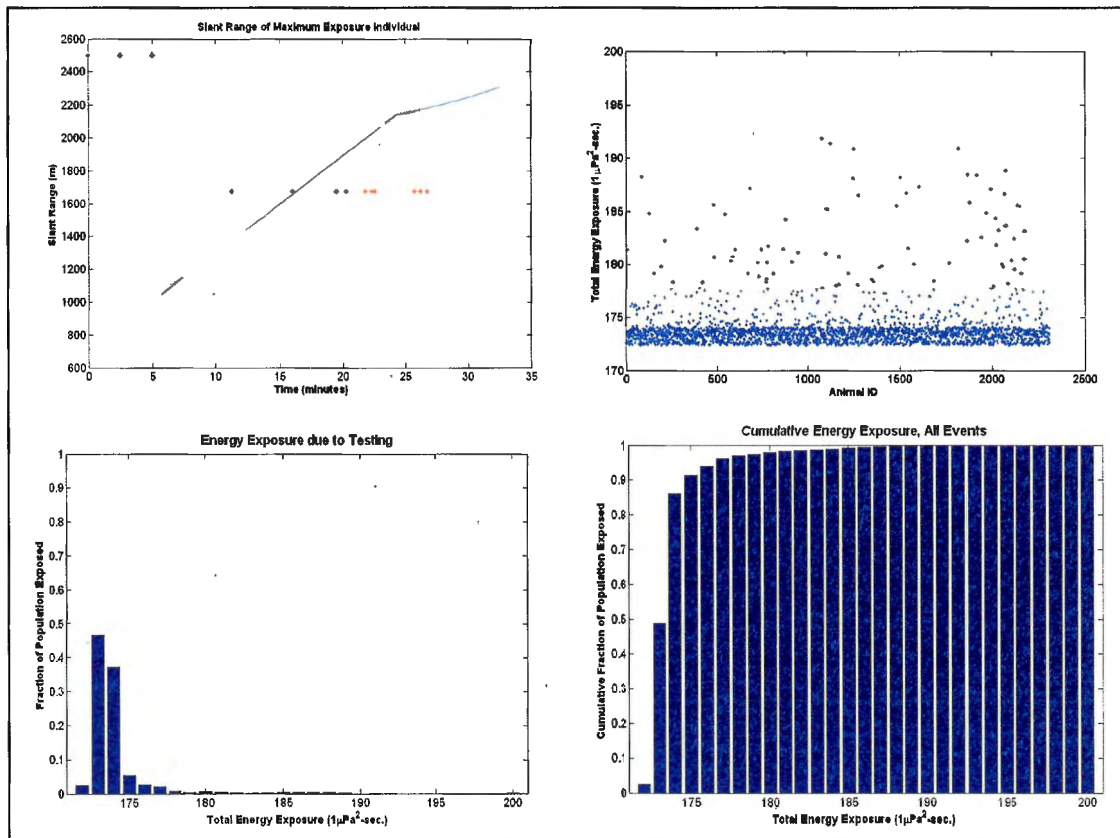


Figure-8. Analysis of Dosimeter Record for Complete Exercise

SUMMARY

A flexible simulation tool has been developed to access the exposures of marine mammals to underwater explosions and can be used in other types of acoustic sources with use of the appropriate propagation models. Analysis of the dosimeter record allows the effect of avoidance behavior, mammal movement characteristics, hearing recovery and the impact on exposure statistics. Being modular in nature, the fidelity of the simulation will increase as more is learned about the hearing and behavioral reactions to acoustic events. Test planners may also be able to use this tool to plan tests that minimize impacts to the marine mammal population.

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